

21cm CRT Telescope Design

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Design Process

- Define the science
 - Dark energy
- Define parameter that measures success
 - Dark Energy Task force Figure of Merit
- Define science technique
 - Baryon Acoustic Oscillations with intensity mapping
 - To peer deep into large red-shifts, we use a hydrogen hyperfine transition at 1.42 GHz to make a 3-D radio intensity map of the universe
 - By intensity map, we mean that galaxies are not spatially resolved
- Pick an Instrument
 - Develop a rough engineering model
 - Estimate the cost versus science of the instrument
 - Pick a parameter set or “punt”

INSTRUMENT CHOICE

FFT Radio Telescopes

- 3-D sky surveys require
 - Large collecting area
 - Good resolution
 - Large frequency bandwidth
 - High speed
- For a given sensitivity, the survey speed is proportional to the number of electronic channels.
 - We will show (using Hee-Jong's analysis) that to do a Stage 3-4 Dark Energy experiment using BAO in 2-3 years, you will need ~2000 channels.
- We think the best fit for these requirements is a FFT Radio Telescope¹
- An FFT Radio Telescope is composed of:
 - arrays of low gain, wide beam width, antennae
 - connected to low-noise, high speed, electronics.

¹Omniscopes: Large Area Telescope Arrays with only $N \log N$ Computational Cost, M. Tegmark - <http://arxiv.org/abs/0909.0001v1>

Visibilities

- A standard radio interferometer measures information(visibility) from the cross correlation of 2 receivers as a function of the distance between receivers.
 - For an array of N receivers, there are $N(N-1)/2$ possible products to compute.
 - For $N=2000$, there are $\sim 2 \times 10^6$ visibilities
- For an FFT Radio Telescope
 - Receivers are located uniformly in an array
 - N electronic beams are formed on the sky simultaneously by computing the spatial Fourier transform of the receivers' voltages.
 - The power spectrum of each electronic beam contains all the possible visibilities.
 - The computational load goes as $N \log N$
 - But because of the uniform spacing required for spatial Fourier Transform, there are many redundant baselines.
 - However, these redundant baselines provide:
 - Better signal to noise (for quick survey speed)
 - Flexibility for calibration or insensitivity to calibration errors.

New Technology

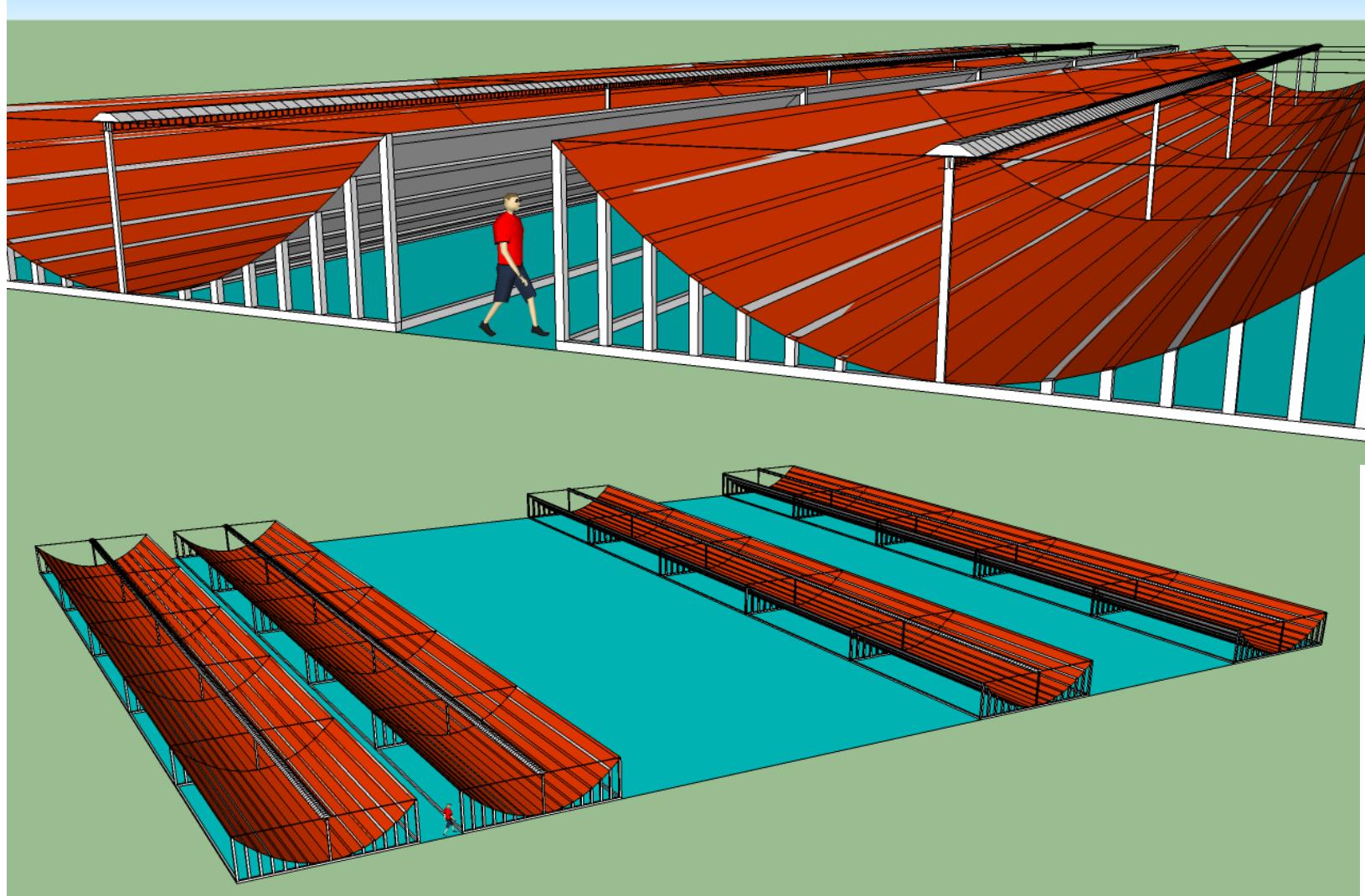
- FFT Radio Telescopes are just recently possible because of:
 - Advances in room temperature, wideband, low noise electronics developed for the cell phone industry
 - High speed transmission (fiber optics, gigabit ethernet, etc.)
 - Availability of low cost, high-speed data processors
 - FFT Processing ($n \log(n)$)
 - Field Gate Programmable Arrays (FGPA's)
 - Graphical Processing Units (GPU's)

The 21cm Cylindrical Radio Telescope (CRT)

- To reduce cost (as a tradeoff of survey speed), the CRT takes the FFT Radio Telescope concept one step further by arranging the CRT as an 2-D collection of 1-D arrays operating in drift-scan mode.²
 - The 1-D arrays sit at the focal point of cylindrical reflectors aligned to the meridian
 - The CRT consists of at least 2 cylinders
 - Each cylinder is ranges from 75-150m in length by 10-20m in width
 - Each cylinder has on the order of 256-512 channels per polarization
 - Operating at a frequency range of 500-1000MHz
 - Each cylinder costs on the order of 2-5M\$

²The Hubble Sphere Hydrogen Survey, J Peterson , K. Bandura, U. Pen -arXiv:astro-ph/0606104

CRT Concept



Pittsburgh Prototype

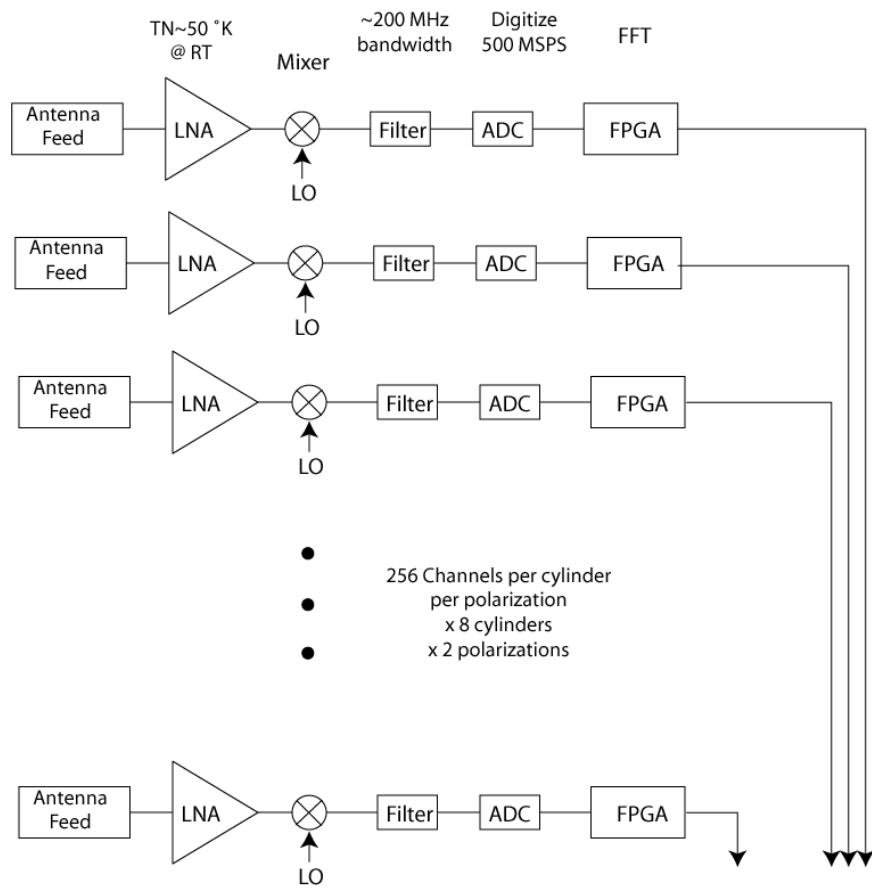


The 21cm Cylindrical Radio Telescope (CRT)

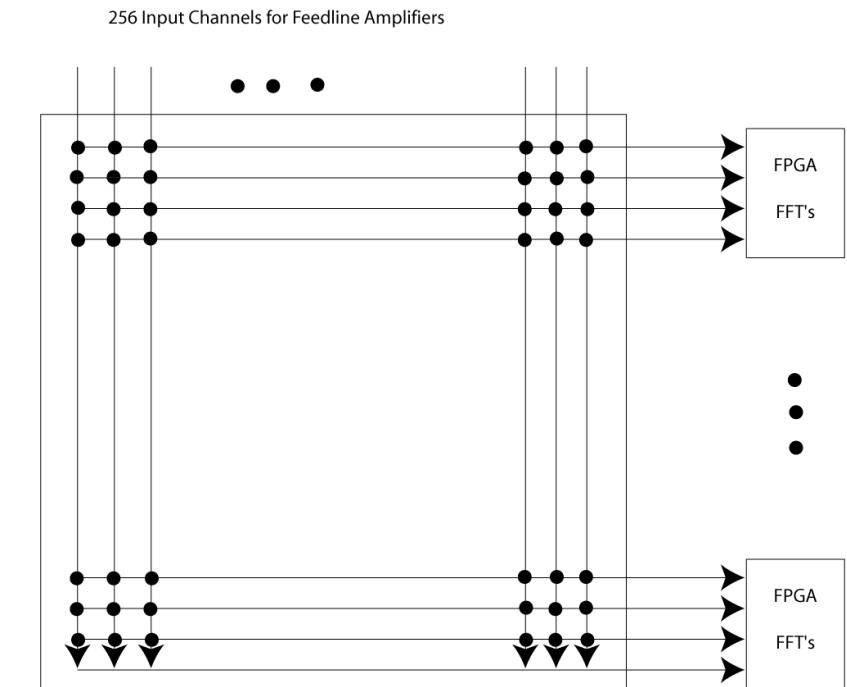
- The cylinders are oriented north-south and focus the beam in the east west direction with a beam width of 1.5-3 degrees.
- A feed array of 256-512 uniformly spaced receivers (spacing ~0.3m) sits along the focal point of the cylinder.
- A spatial Fourier transform of the N receiver voltages along a given cylinder produces a fan of N beams for that cylinder
- The kth “visibility” is formed by taking the product of the kth beam from Cylinder A with the kth beam of Cylinder B
- At each frequency bin, the kth “visibility” for all N beams for all possible cylinder pairs is time averaged and recorded.
- The nominal number of cylinders is four.
 - The cylinders are not uniformly spaced in the east-west direction.
 - They are located at positions 1,2,5, & 7 to form 6 effective visibilities for each kth beam.

Signal Processing

1st Stage



2nd Stage



CRT Advantages

- Low cost
 - Focusing in one direction
 - no moving parts
 - Maintenance & operation advantage (no moving parts)
- Higher stability
 - fixed w.r.t. ground (side-lobes do not change)
 - instrument response averages over right ascension
 - Reflector consistency - gravity is constant
 - Experience at other large radio telescopes show that drift scanning provides the superior stability that is required for large area surveys.

REQUIREMENTS

Frequency Bands

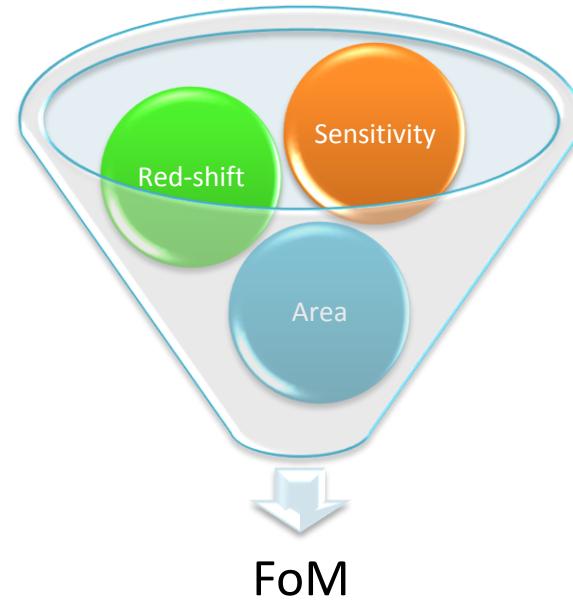
- Divide survey into two by dividing frequency span into two bands
 - Performance maximized by noise performance
 - Noise match easier over smaller bandwidth
 - Larger digitizer dynamic range for smaller bandwidth
- Bands are adjacent
- Fractional bandwidth of each band < 33%
- Limit the maximum span to half the digitizer bandwidth
- Digital electronics are re-used for each band
- Number of electronic channels are the same for both bands
- Reflector width and spacing the same for both bands

Parameter Set

- Scientific Parameters (SCI)
- Static Engineering Parameters (STE)
- Dynamic Engineering Parameters (DYE)
- Derived Engineering Parameters (DRE)

Scientific Parameters (SCI) (a.k.a. the 5 magic numbers)

- We want to have a set of numbers that
 - Describe the science
 - Can be derived from **ANY** telescope configuration
- The magic numbers for determining dark energy parameters using BAO
 - Minimum red-shift
 - Maximum red-shift
 - Survey area
 - Pixel Resolution
 - Pixel Sensitivity



Scientific Parameters (SCI)

| Number | Description | Symbol |
|--------|--|--------------|
| SCI.01 | Maximum Red-shift | z_{max} |
| SCI.02 | Minimum Red-shift | z_{min} |
| SCI.03 | Angular Resolution | $\delta\psi$ |
| SCI.04 | Survey Area | A_s |
| SCI.05 | Sensitivity per Pixel | δT_p |
| SCI.06 | Figure of Merit with Plank Priors | FoM_p |
| SCI.07 | Figure of Merit with Stage II Dark Energy Priors | FoM_{II} |

Scientific Parameters (SCI)

$$z_{min\pm} = \frac{1.42GHz}{F_{c\pm} - \frac{1}{2}\Delta F_{\pm}} - 1$$

$$M_{d\pm} = \frac{2\Delta F_{\pm}}{\delta f_{\pm}}$$

$$z_{\pm} = \frac{1.42GHz}{F_{c\pm}} - 1$$

$$A = \int_0^{2\pi} d\phi \int_{\theta_{d\min}}^{\theta_{d\max}} \cos(\theta) d\theta = 2\pi [\sin(\theta_{d\max}) - \sin(\theta_{d\min})]$$

$$z_{max\pm} = \frac{1.42GHz}{F_{c\pm} + \frac{1}{2}\Delta F_{\pm}} - 1$$

$$\sin(\delta\psi_{\pm}) = \frac{\lambda}{N_f d_{f\pm}}$$

$$\delta z_{\pm} \approx 0.436 \times \delta\psi_{\pm} (\text{radians}) \times z_{\pm} (z_{\pm} + 2)$$

$$\delta f_{\pm} = \frac{1.4GHz}{(1+z_{\pm})^2} \delta z_{\pm}$$

$$\theta_{d\max} = \alpha_L + \frac{\Delta\theta_d}{2} \quad \text{if} \quad \alpha_L + \frac{\Delta\theta_d}{2} < \frac{\pi}{2}$$

$$\theta_{d\max} = \frac{\pi}{2} \quad \text{if} \quad \alpha_L + \frac{\Delta\theta_d}{2} > \frac{\pi}{2}$$

$$\theta_{d\min} = \alpha_L - \frac{\Delta\theta_d}{2} \quad \text{if} \quad \alpha_L - \frac{\Delta\theta_d}{2} < -\frac{\pi}{2}$$

$$\theta_{d\min} = -\frac{\pi}{2} \quad \text{if} \quad \alpha_L - \frac{\Delta\theta_d}{2} < -\frac{\pi}{2}$$

Scientific Parameters (SCI)

$$\sin(\psi_n) = \left(-\frac{1}{2} + \frac{n}{N_f} \right) \frac{\lambda}{d_f}$$

$$\theta_n = \psi_n + \alpha_L$$

$$\Delta\phi_C = \frac{\lambda}{W_c}$$

$$\sin\left(\frac{\Delta\varphi_{RA_n}}{2}\right) = \frac{1}{\cos(\theta_n)} \sin\left(\frac{\Delta\phi_C}{2}\right)$$

$$\tau_p = \frac{\tau_s D_f}{N_f + 1} \sum_{n=0}^{N_f} \frac{\Delta\varphi_{RA_n}}{2\pi}$$

$$\delta T_{p\pm} = \frac{1}{\sqrt{\tau_{p\pm} \delta f_\pm}} \left(T_s + \frac{1}{g_a} \frac{1}{p_{f\pm}} \frac{d_{f\pm}}{h_{f\pm}} \sqrt{\frac{N_f}{(N_f - 1)}} \sqrt{\frac{N_c}{(N_c - 1)}} T_A \right)$$

Static Engineering Parameters (STE)

- The static engineering parameters are independent parameters that are
 - important in describing the telescope
 - not easily changed for design optimization
- such as the latitude of the telescope site, amplifier temperature, etc.

Static Engineering Parameters (STE)

| Number | Description | Symbol |
|--------|---------------------------------------|--------------------|
| STE.01 | Survey Time | τ_s |
| STE.02 | Observing Duty Factor | D_f |
| STE.03 | Latitude of telescope site | α_L |
| STE.04 | Average Sky Temperature | T_s |
| STE.05 | Maximum Frequency Span per band | $\Delta F_{b\max}$ |
| STE.06 | Maximum Fractional Bandwidth per band | δf_b |
| STE.07 | Number of Polarizations | N_p |
| STE.08 | Antenna Feed Power Efficiency | g_a |
| STE.09 | Cylinder Width / Cylinder Spacing | x_{cyl} |
| STE.10 | Equivalent Amplifier Temperature | T_A |
| STE.11 | Electronics Cost per Channel | R_e |
| STE.12 | Feed Structure Cost per meter | R_f |
| STE.13 | Reflector Cost per Cylinder volume | R_r |

Dynamic Engineering Parameters (DYE)

- Dynamic engineering parameters are independent parameters that can be easily varied during the design stage
 - such as feed spacing and the number of channels per cylinder

| Number | Description | Symbol |
|--------|--|--------|
| DYE.01 | Center Frequency of both bands combined | F_c |
| DYE.02 | Average Feed Spacing | D_f |
| DYE.03 | Number of digital channels per cylinder per polarization | N_f |
| DYE.04 | Average Number of possible cylinder locations | N_L |
| DYE.05 | Average Cylinder packing factor | p_f |
| DYE.06 | Target Cost | C_T |

Derived Engineering Parameters (DRE)

- Derived engineering parameters are design specific parameters
 - such as cylinder length and width
 - but are derived from the static and dynamic engineering parameters.

Derived Engineering Parameters (DRE)

| Number | Description | Symbol |
|--------|-------------------------------------|------------------|
| DRE.01 | Number of Cylinders | N_c |
| DRE.02 | Cylinder Length | L_c |
| DRE.03 | Cylinder Width | W_c |
| DRE.04 | Cylinder Spacing | S_c |
| DRE.05 | Declination Span | $\Delta\theta_d$ |
| DRE.06 | Feed Length | h_f |
| DRE.07 | Feed Spacing | d_f |
| DRE.08 | Band Center Frequency | F_{cb} |
| DRE.09 | Wavelength | λ |
| DRE.10 | Band Frequency Span | ΔF_b |
| DRE.11 | Resolution Bandwidth | δf |
| DRE.12 | Minimum Digital Memory | M_d |
| DRE.14 | Integration Time per Pixel | τ_p |
| DRE.15 | Number of Channels per polarization | N_{fT} |
| DRE.16 | Electronics Cost | C_e |
| DRE.17 | Feed Structure Cost | C_f |
| DRE.18 | Reflector Cost | C_R |
| DRE.19 | Total Cost | C_T |

Derived Engineering Parameters (DRE)

$$\delta_f < \frac{F_c}{\Delta F_{bmax}} - \frac{2}{1 + \sqrt{\frac{4F_c - \Delta F_{bmax}}{2F_c}}}$$

$$F_{c\pm} = F_c \frac{4 \pm 2\delta_f}{4 + \delta_f^2}$$

$$\Delta F_{\pm} = \delta_f F_{c\pm}$$

$$N_{L\pm} = round\left(N_L \frac{F_c}{F_{c\pm}}\right)$$

$$d_{f\pm} = D_f N_{L\pm}$$

$$p_{f+} = p_{f-} \frac{N_{L-}}{N_{L+}}$$

$$N_{f+} = N_{f-} = N_f$$

$$N_{C+} = N_{C-} = N_C = p_{f-} N_{L-}$$

$$R_{\pm} = \frac{1}{2} \frac{N_C (N_C - 1)}{N_{L\pm} - 1}$$

$$N_C > \frac{1}{2} \left(1 + \sqrt{1 + 8(N_{L-} - 1)} \right)$$

$$p_{f-} > \frac{1}{2N_{L-}} \left(1 + \sqrt{1 + 8(N_{L-} - 1)} \right)$$

$$L_{C\pm} = N_f d_{f\pm}$$

$$W_C = x_{cyl} S_C = x_{cyl} \frac{N_f d_{f\pm}}{N_{L\pm}}$$

$$\sin\left(\frac{\Delta\theta_{d\pm}}{2}\right) = \frac{\lambda}{2d_{f\pm}}$$

$$A_f = h_f W_C$$

$$\sin\left(\frac{\Delta\theta_f}{2}\right) = \frac{\lambda}{2h_f}$$

$$h_{f\pm} = d_{f\pm}$$

Telescope Cost

- It is not intended that these costs include everything that would arise in designing and building a large radio telescope
 - such as site preparation, non-recoverable engineering costs, overhead, contingency etc.,
- These costs should only be used in trying to compare sets of design parameters.
- The cost of the digital electronics is assumed to scale only with the number of feeds:

$$C_e = N_f N_c N_p R_e$$

Telescope Cost

- The cost of the telescope structure is broken into two parts.
- The feed line is the most complicated part of the reflector system and this cost will scale as the total length of the array.

$$C_f = L_c N_c R_f = N_f N_c d_f R_f$$

- The cost of the main reflector surface will not only be proportional to area
 - but height as well since tall structures will be more difficult to build.
 - For a fixed f-ratio, the height will scale with cylinder width.

$$C_r = L_c N_c W_c^2 R_f = N_f N_c d_f W_c^2 R_f$$



STRAWMAN DESIGNS

Requirement Optimization

- The purpose of the CRT collaboration is to develop a pre-conceptual design report that describe the “strawman” design
 - This work is in progress.
 - For the purpose of the review we will outline a couple of “strawman” design possibilities.
- To focus the collaboration we have developed a web application to evaluate parameter sets
 - Uses Hee-Jong’s BAO analysis technique for determining Figure of Merit
 - Web application has two features
 - Evaluator
 - Optimizer

Requirement Optimizer

- Vary
 - Center Frequency
 - Feed spacing
 - Number of cylinder locations
 - Cylinder packing factor
- Constrain
 - Number of feeds per cylinder to reach target cost

Requirement Web Application

CRT Design Requirements II

Calculate FoM Optimize Iterations 40

| | Band 1 | | | Target | Step | Band 2 | | |
|-------------------------------------|--------|--------|--------|--------|------|--------|--------|--------|
| SCI.01 - Redshift Range | 1.8 | 1.33 | 1 | | | 1 | 0.67 | 0.43 |
| SCI.02 | | | | | | 3.64 | 3.05 | 2.58 |
| SCI.03 Survey Area | 3.64 | 2.81 | 2.41 | | | 18.33 | 15.28 | 13.09 |
| SCI.04 Angular Resolution | 17.11 | 14.26 | 12.22 | | | 74.76 | 91.53 | 172.33 |
| SCI.05 Sensitivity per Pixel | 87.37 | 104.74 | 194.42 | | | | | |
| SCI.06 Plank Priors Figure of Merit | | 89.67 | | 89.67 | | | 89.67 | |
| SCI.07 DE II Priors Figure of Merit | | 235.84 | | 235.84 | | | 235.84 | |

| | | | | | |
|---|--------|------|----|--------|--------|
| DYE.01 Center Frequency | 600 | 740 | 0 | 840 | MHz |
| DYE.02 Feed Spacing | 0.5838 | 0.6 | 0 | 0.5449 | lambda |
| DYE.03 Digital Channels per Cylinder per Polarization | 413 | 413 | | 413 | |
| DYE.04 Number of Cylinder locations | 6 | 5 | 2 | 4 | |
| DYE.05 Cylinder Packing Factor | 66.67 | 60 | 20 | 100 | % |
| DYE.06 Total Cost | 15.01 | 15.0 | | 13.31 | M\$ |

| | | | | | |
|------------------------------|----|------|--|----|---------|
| STE.01 Survey Time | 2 | 2.0 | | 2 | years |
| STE.02 Observing Duty Factor | 50 | 50.0 | | 50 | % |
| STE.03 Latitude | 35 | 35.0 | | 35 | degrees |

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Requirement Web Application

| Requirement | Value | Unit | Value | Unit | Value | Unit | Value | Unit |
|--|--------|------|--------|------|-------|------|------------------------|---------|
| STE.08 Antenna Efficiency | 80 | | 80.0 | | 80 | | % | |
| STE.09 Antenna Width Fill Factor | 80 | | 80.0 | | 80 | | % | |
| STE.10 Amplifier Temperature | 50 | | 50.0 | | 50 | | K | |
| STE.11 Electronics Cost per Channel | 3000 | | 3000.0 | | 3000 | | \$ | |
| STE.12 Feed Structure Cost Rate | 2300 | | 2300.0 | | 2300 | | \$/meter | |
| STE.13 Reflector Volume Cost Rate | 32 | | 32.0 | | 32 | | \$/meter ^{^3} | |
| DRE.01 Number of Cylinders | 4 | | | | 4 | | | |
| DRE.02 Cylinder Length | 120.55 | | | | 80.37 | | meters | |
| DRE.03 Cylinder Width | 16.07 | | | | 16.07 | | meters | |
| DRE.04 Cylinder Spacing | 20.09 | | | | 20.09 | | meters | |
| DRE.05 Declination Span | 180 | | 117.85 | | 180 | | 103.73 | degrees |
| DRE.06 Feed Length | | | 29.19 | | | | 19.46 | cm |
| DRE.07 Feed Spacing | | | 29.19 | | | | 19.46 | cm |
| DRE.08 Frequency | 500 | | 600 | | 700 | | 980 | MHz |
| DRE.09 Wavelength | 60 | | 50 | | 42.86 | | 30.61 | cm |
| DRE.10 Frequency Span | | | 200 | | | | 280 | MHz |
| DRE.11 Res. Bandwidth | 2.65 | | 2.07 | | 1.63 | | 1.18 | MHz |
| DRE.12 Minimum Digital Memory | | | 245 | | | | 472 | |
| DRE.13 Integration Time per Pixel | 8.02 | | 7.16 | | 2.64 | | 2.23 | days |
| DRE.14 Number of Channels per polarization | | | 1652 | | | | 1652 | |
| DRE.15 Electronics Cost | | | 9.91 | | | | 9.91 | M\$ |
| DRE.16 Feed Structure Cost | | | 1.11 | | | | 0.74 | M\$ |
| DRE.17 Reflector Volume Cost | | | 3.99 | | | | 2.66 | M\$ |

Scientific Parameters

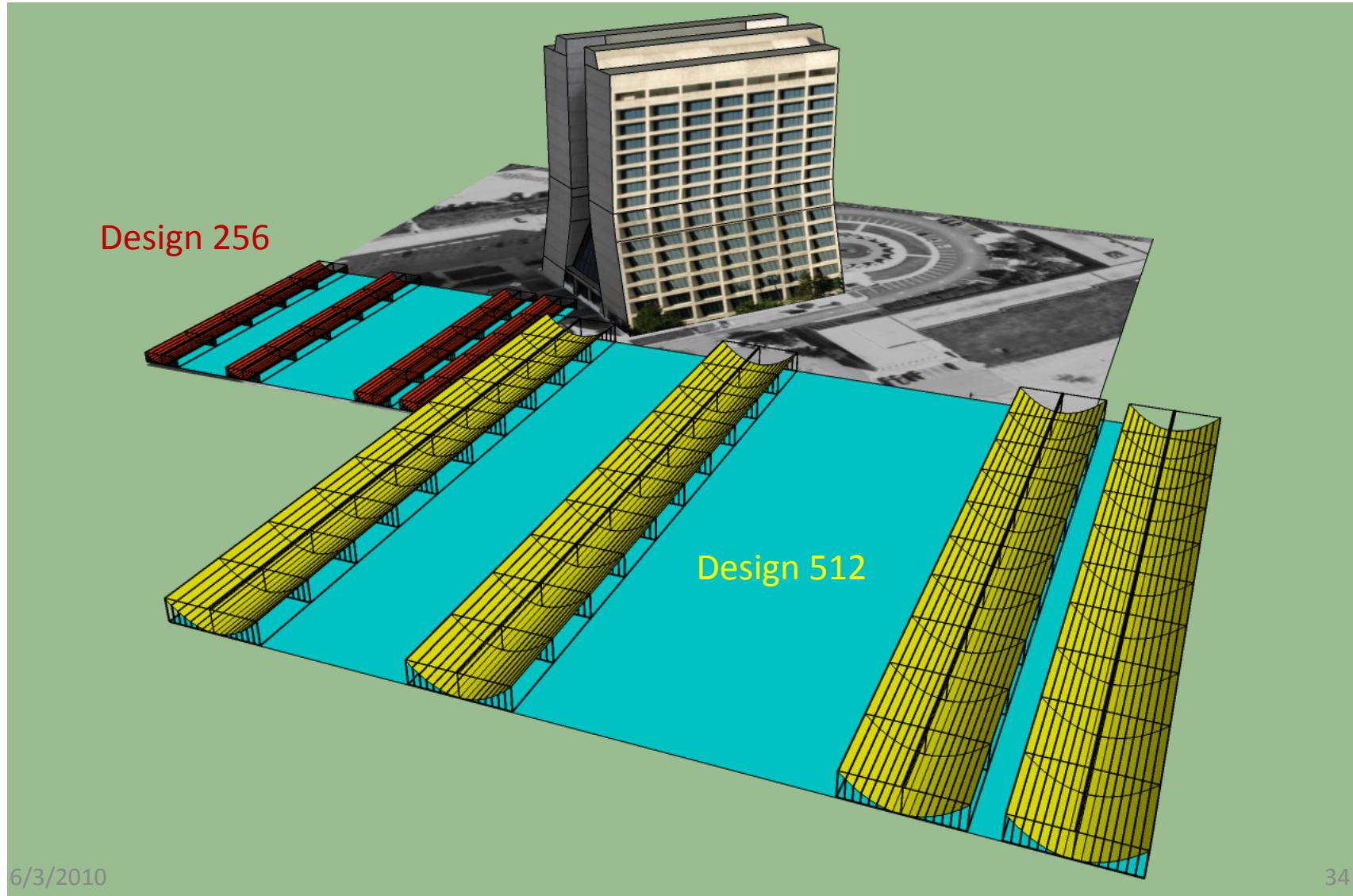
| Cost | 64C66 | 64C133 | 64C200 | 64C266 | 128C66 | 128C133 | 128C200 | 128C266 | 256C66 | 256C133 | 256C200 | 256C266 | 512C66 | 512C133 | 512C200 | 512C266 | M\$ |
|-------------|------------------------------|--------|--------|--------|--------|---------|---------|---------|--------|---------|---------|---------|--------|---------|---------|---------|----------|
| SCI.01 - SC | Redshift Range | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | pi-Ster. |
| SCI.03 | Survey Area | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | 2.81 | arc-min |
| SCI.04 | Angular Resolution | 92.01 | 92.01 | 92.01 | 92.01 | 46.01 | 46.01 | 46.01 | 46.01 | 23 | 23 | 23 | 23 | 11.5 | 11.5 | 11.5 | 11.5 |
| SCI.05 | Sensitivity per Pixel | 19.72 | 10.02 | 7.1 | 5.7 | 36.16 | 18.37 | 13.03 | 10.45 | 68.2 | 34.66 | 24.58 | 19.72 | 127.91 | 65.01 | 46.11 | 36.99 |
| SCI.06 | Plank Priors Figure of Merit | 3.98 | 11.18 | 16.28 | 20.77 | 17.05 | 53.68 | 71.23 | 87.2 | 62.05 | 128.04 | 152.87 | 184.45 | 114.99 | 184.35 | 236.41 | 241.13 |
| SCI.07 | DE II Priors Figure of Merit | 70.58 | 93.44 | 104.56 | 112.2 | 113.22 | 174.25 | 201.21 | 233.86 | 196.07 | 293.45 | 337.03 | 388.93 | 272.45 | 387.34 | 465.85 | 472.79 |

Band 1

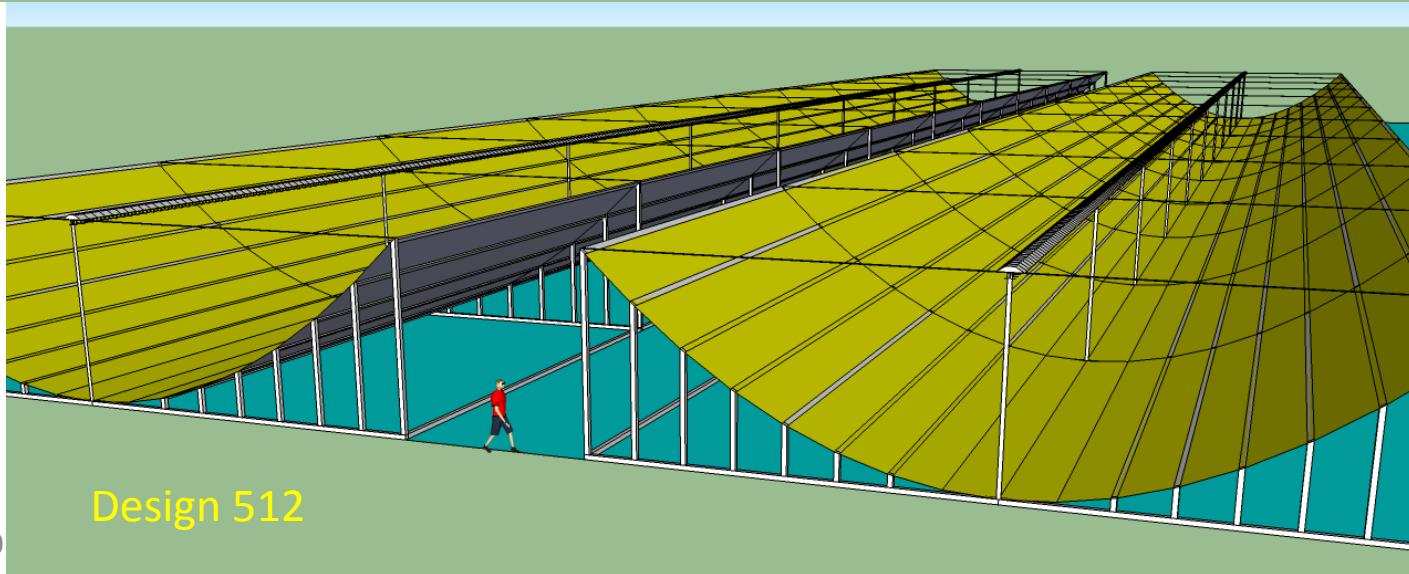
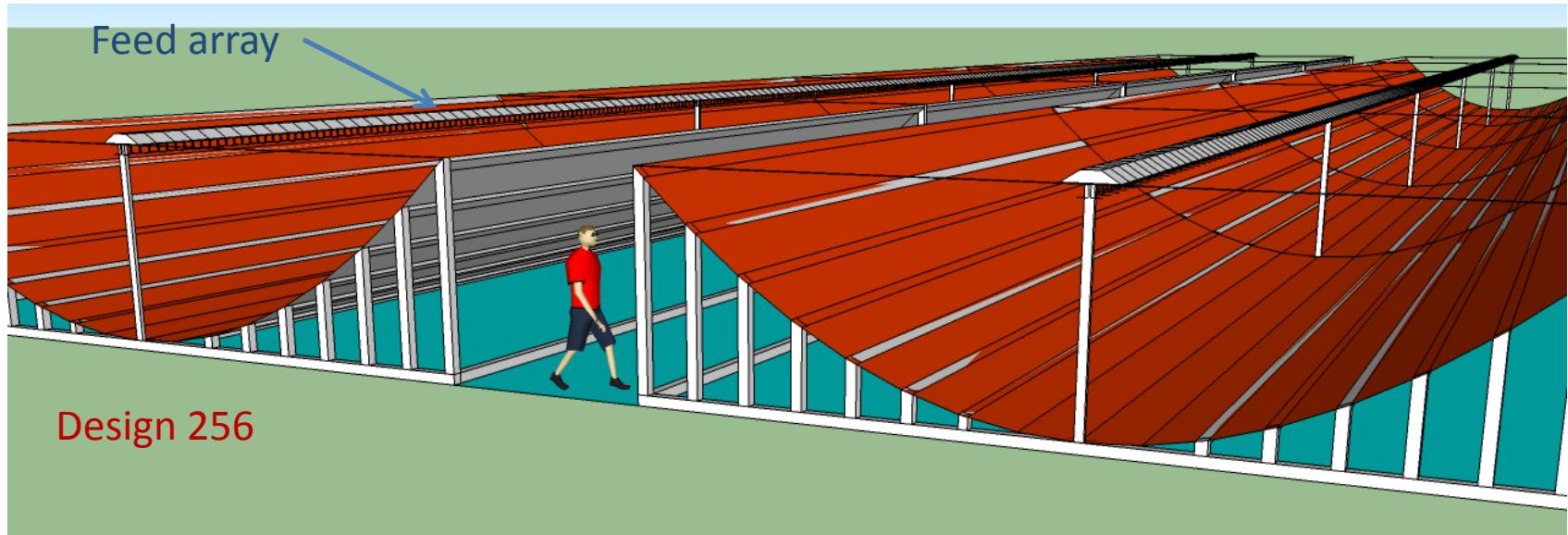
| Cost | 64C66 | 64C133 | 64C200 | 64C266 | 128C66 | 128C133 | 128C200 | 128C266 | 256C66 | 256C133 | 256C200 | 256C266 | 512C66 | 512C133 | 512C200 | 512C266 | M\$ |
|-------------|------------------------------|--------|--------|--------|--------|---------|---------|---------|--------|---------|---------|---------|--------|---------|---------|---------|----------|
| SCI.01 - SC | Redshift Range | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | pi-Ster. |
| SCI.03 | Survey Area | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | arc-min |
| SCI.04 | Angular Resolution | 98.58 | 98.58 | 98.58 | 98.58 | 49.29 | 49.29 | 49.29 | 49.29 | 24.65 | 24.65 | 24.65 | 24.65 | 12.32 | 12.32 | 12.32 | 12.32 |
| SCI.05 | Sensitivity per Pixel | 16.69 | 8.81 | 6.44 | 5.3 | 31.27 | 16.51 | 12.08 | 9.94 | 58.84 | 31.08 | 22.73 | 18.71 | 111.62 | 58.96 | 43.13 | 35.5 |
| SCI.06 | Plank Priors Figure of Merit | 3.98 | 11.18 | 16.28 | 20.77 | 17.05 | 53.68 | 71.23 | 87.2 | 62.05 | 128.04 | 152.87 | 184.45 | 114.99 | 184.35 | 236.41 | 241.13 |
| SCI.07 | DE II Priors Figure of Merit | 70.58 | 93.44 | 104.56 | 112.2 | 113.22 | 174.25 | 201.21 | 233.86 | 196.07 | 293.45 | 337.03 | 388.93 | 272.45 | 387.34 | 465.85 | 472.79 |

Band 2

CRT Strawman Designs



CRT Strawman Designs



Dynamic Engineering Parameters

| | Cost | 64C66 | 64C133 | 64C200 | 64C266 | 128C66 | 128C133 | 128C200 | 128C266 | 256C66 | 256C133 | 256C200 | 256C266 | 512C66 | 12C133 | 512C200 | 512C266 | M\$ |
|--------|-------------------------------|--------|--------|--------|--------|--------|---------|---------|---------|--------|---------|---------|---------|--------|--------|---------|---------|--------|
| DYE.01 | Center Frequency | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | MHz |
| DYE.02 | Feed Spacing | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | 0.5838 | lambda |
| DYE.03 | Digital Channels per Cylinder | 64 | 64 | 64 | 64 | 128 | 128 | 128 | 128 | 256 | 256 | 256 | 256 | 512 | 512 | 512 | 512 | |
| DYE.04 | Number of Cylinder locations | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | |
| DYE.05 | Cylinder Packing Factor | 66.67 | 133.33 | 200 | 266.67 | 66.67 | 133.33 | 200 | 266.67 | 66.67 | 133.33 | 200 | 266.67 | 66.67 | 133.33 | 200 | 266.67 | % |
| DYE.06 | Total Cost | 1.72 | 3.45 | 5.17 | 6.89 | 3.53 | 7.07 | 10.6 | 14.14 | 7.78 | 15.56 | 23.34 | 31.12 | 21.26 | 42.52 | 63.78 | 85.03 | M\$ |

Band 1

| | Cost | 64C66 | 64C133 | 64C200 | 64C266 | 128C66 | 128C133 | 128C200 | 128C266 | 256C66 | 256C133 | 256C200 | 256C266 | 512C66 | 12C133 | 512C200 | 512C266 | M\$ |
|--------|-------------------------------|--------|--------|--------|--------|--------|---------|---------|---------|--------|---------|---------|---------|--------|--------|---------|---------|--------|
| DYE.01 | Center Frequency | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | MHz |
| DYE.02 | Feed Spacing | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | 0.5449 | lambda |
| DYE.03 | Digital Channels per Cylinder | 64 | 64 | 64 | 64 | 128 | 128 | 128 | 128 | 256 | 256 | 256 | 256 | 512 | 512 | 512 | 512 | |
| DYE.04 | Number of Cylinder locations | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | |
| DYE.05 | Cylinder Packing Factor | 100 | 200 | 300 | 400 | 100 | 200 | 300 | 400 | 100 | 200 | 300 | 400 | 100 | 200 | 300 | 400 | % |
| DYE.06 | Total Cost | 1.66 | 3.32 | 4.98 | 6.64 | 3.38 | 6.76 | 10.14 | 13.52 | 7.24 | 14.47 | 21.71 | 28.94 | 18.27 | 36.54 | 54.81 | 73.07 | M\$ |

Band 2

Derived Engineering Parameters

Band 1

| Cost | 64C66 | 64C133 | 64C200 | 64C266 | 128C66 | 128C133 | 128C200 | 128C266 | 256C66 | 256C133 | 256C200 | 256C266 | 512C66 | 12C133 | 512C200 | 512C266 | M\$ | |
|--------|----------------------------|--------|--------|--------|--------|---------|---------|---------|--------|---------|---------|---------|--------|--------|---------|---------|--------|---------|
| DRE.01 | Number of Cylinders | 4 | 8 | 12 | 16 | 4 | 8 | 12 | 16 | 4 | 8 | 12 | 16 | 4 | 8 | 12 | 16 | |
| DRE.02 | Cylinder Length | 18.68 | 18.68 | 18.68 | 18.68 | 37.36 | 37.36 | 37.36 | 37.36 | 74.72 | 74.72 | 74.72 | 74.72 | 149.45 | 149.45 | 149.45 | 149.45 | meters |
| DRE.03 | Cylinder Width | 2.49 | 2.49 | 2.49 | 2.49 | 4.98 | 4.98 | 4.98 | 4.98 | 9.96 | 9.96 | 9.96 | 9.96 | 19.93 | 19.93 | 19.93 | 19.93 | meters |
| DRE.04 | Cylinder Spacing | 3.11 | 3.11 | 3.11 | 3.11 | 6.23 | 6.23 | 6.23 | 6.23 | 12.45 | 12.45 | 12.45 | 12.45 | 24.91 | 24.91 | 24.91 | 24.91 | meters |
| DRE.05 | Declination Span | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | 117.85 | degrees |
| DRE.06 | Feed Length | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | cm |
| DRE.07 | Feed Spacing | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | 29.19 | cm |
| DRE.08 | Frequency | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | MHz |
| DRE.09 | Wavelength | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | cm |
| DRE.10 | Frequency Span | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | MHz |
| DRE.11 | Res. Bandwidth | 13.33 | 13.33 | 13.33 | 13.33 | 6.66 | 6.66 | 6.66 | 6.66 | 3.33 | 3.33 | 3.33 | 3.33 | 1.67 | 1.67 | 1.67 | 1.67 | MHz |
| DRE.12 | Minimum Digital Memory | 38 | 38 | 38 | 38 | 76 | 76 | 76 | 76 | 152 | 152 | 152 | 152 | 304 | 304 | 304 | 304 | |
| DRE.13 | Integration Time per Pixel | 31.67 | 31.67 | 31.67 | 31.67 | 18.71 | 18.71 | 18.71 | 18.71 | 10.48 | 10.48 | 10.48 | 10.48 | 5.95 | 5.95 | 5.95 | 5.95 | days |
| DRE.14 | Number of Channels | 256 | 512 | 768 | 1024 | 512 | 1024 | 1536 | 2048 | 1024 | 2048 | 3072 | 4096 | 2048 | 4096 | 6144 | 8192 | |
| DRE.15 | Electronics Cost | 1.54 | 3.07 | 4.61 | 6.14 | 3.07 | 6.14 | 9.22 | 12.29 | 6.14 | 12.29 | 18.43 | 24.58 | 12.29 | 24.58 | 36.86 | 49.15 | M\$ |
| DRE.16 | Feed Structure Cost | 0.17 | 0.34 | 0.52 | 0.69 | 0.34 | 0.69 | 1.03 | 1.37 | 0.69 | 1.37 | 2.06 | 2.75 | 1.37 | 2.75 | 4.12 | 5.5 | M\$ |
| DRE.17 | Reflector Volume Cost | 0.01 | 0.03 | 0.04 | 0.06 | 0.12 | 0.24 | 0.36 | 0.47 | 0.95 | 1.9 | 2.85 | 3.8 | 7.6 | 15.19 | 22.79 | 30.38 | M\$ |

Band 2

| Cost | 64C66 | 64C133 | 64C200 | 64C266 | 128C66 | 128C133 | 128C200 | 128C266 | 256C66 | 256C133 | 256C200 | 256C266 | 512C66 | 12C133 | 512C200 | 512C266 | M\$ | |
|--------|----------------------------|--------|--------|--------|--------|---------|---------|---------|--------|---------|---------|---------|--------|--------|---------|---------|--------|---------|
| DRE.01 | Number of Cylinders | 4 | 8 | 12 | 16 | 4 | 8 | 12 | 16 | 4 | 8 | 12 | 16 | 4 | 8 | 12 | 16 | |
| DRE.02 | Cylinder Length | 12.45 | 12.45 | 12.45 | 12.45 | 24.91 | 24.91 | 24.91 | 24.91 | 49.82 | 49.82 | 49.82 | 49.82 | 99.63 | 99.63 | 99.63 | 99.63 | meters |
| DRE.03 | Cylinder Width | 2.49 | 2.49 | 2.49 | 2.49 | 4.98 | 4.98 | 4.98 | 4.98 | 9.96 | 9.96 | 9.96 | 9.96 | 19.93 | 19.93 | 19.93 | 19.93 | meters |
| DRE.04 | Cylinder Spacing | 3.11 | 3.11 | 3.11 | 3.11 | 6.23 | 6.23 | 6.23 | 6.23 | 12.45 | 12.45 | 12.45 | 12.45 | 24.91 | 24.91 | 24.91 | 24.91 | meters |
| DRE.05 | Declination Span | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | 133.17 | degrees |
| DRE.06 | Feed Length | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | cm |
| DRE.07 | Feed Spacing | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | 19.46 | cm |
| DRE.08 | Frequency | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | 840 | MHz |
| DRE.09 | Wavelength | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | 35.71 | cm |
| DRE.10 | Frequency Span | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | 280 | MHz |
| DRE.11 | Res. Bandwidth | 11.2 | 11.2 | 11.2 | 11.2 | 5.6 | 5.6 | 5.6 | 5.6 | 2.8 | 2.8 | 2.8 | 2.8 | 1.4 | 1.4 | 1.4 | 1.4 | MHz |
| DRE.12 | Minimum Digital Memory | 73 | 73 | 73 | 73 | 146 | 146 | 146 | 146 | 292 | 292 | 292 | 292 | 585 | 585 | 585 | 585 | |
| DRE.13 | Integration Time per Pixel | 25.42 | 25.42 | 25.42 | 25.42 | 14.38 | 14.38 | 14.38 | 14.38 | 8.09 | 8.09 | 8.09 | 8.09 | 4.49 | 4.49 | 4.49 | 4.49 | days |
| DRE.14 | Number of Channels | 256 | 512 | 768 | 1024 | 512 | 1024 | 1536 | 2048 | 1024 | 2048 | 3072 | 4096 | 2048 | 4096 | 6144 | 8192 | |
| DRE.15 | Electronics Cost | 1.54 | 3.07 | 4.61 | 6.14 | 3.07 | 6.14 | 9.22 | 12.29 | 6.14 | 12.29 | 18.43 | 24.58 | 12.29 | 24.58 | 36.86 | 49.15 | M\$ |
| DRE.16 | Feed Structure Cost | 0.11 | 0.23 | 0.34 | 0.46 | 0.23 | 0.46 | 0.69 | 0.92 | 0.46 | 0.92 | 1.37 | 1.83 | 0.92 | 1.83 | 2.75 | 3.67 | M\$ |
| DRE.17 | Reflector Volume Cost | 0.01 | 0.02 | 0.03 | 0.04 | 0.08 | 0.16 | 0.24 | 0.32 | 0.63 | 1.27 | 1.9 | 2.53 | 5.06 | 10.13 | 15.19 | 20.25 | M\$ |

Static Engineering Parameters

| | Cost | 64C66 | 64C133 | 64C200 | 64C266 | 128C66 | 128C133 | 128C200 | 128C266 | 256C66 | 256C133 | 256C200 | 256C266 | 512C66 | 512C133 | 512C200 | 512C266 | M\$ |
|--------|------------------------------|-------|--------|--------|--------|--------|---------|---------|---------|--------|---------|---------|---------|--------|---------|---------|---------------|-----|
| STE.01 | Survey Time | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 years | |
| STE.02 | Observing Duty Factor | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 % | |
| STE.03 | Latitude | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 degrees | |
| STE.04 | Avg. Sky Temperature | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 K | |
| STE.05 | Maximum Span | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 MHz | |
| STE.06 | Center Freq / Freq Span | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | |
| STE.07 | Number of Polarizations | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | |
| STE.08 | Antenna Efficiency | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 % | |
| STE.09 | Antenna Width Fill Factor | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 % | |
| STE.10 | Amplifier Temperature | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 K | |
| STE.11 | Electronics Cost per Channel | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 \$ | |
| STE.12 | Feed Structure Cost Rate | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 | 2300 \$/meter | |
| STE.13 | Reflector Volume Cost Rate | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 \$/meter^3 | |

Design 256

Design 512

Figure of Merit vs Cost

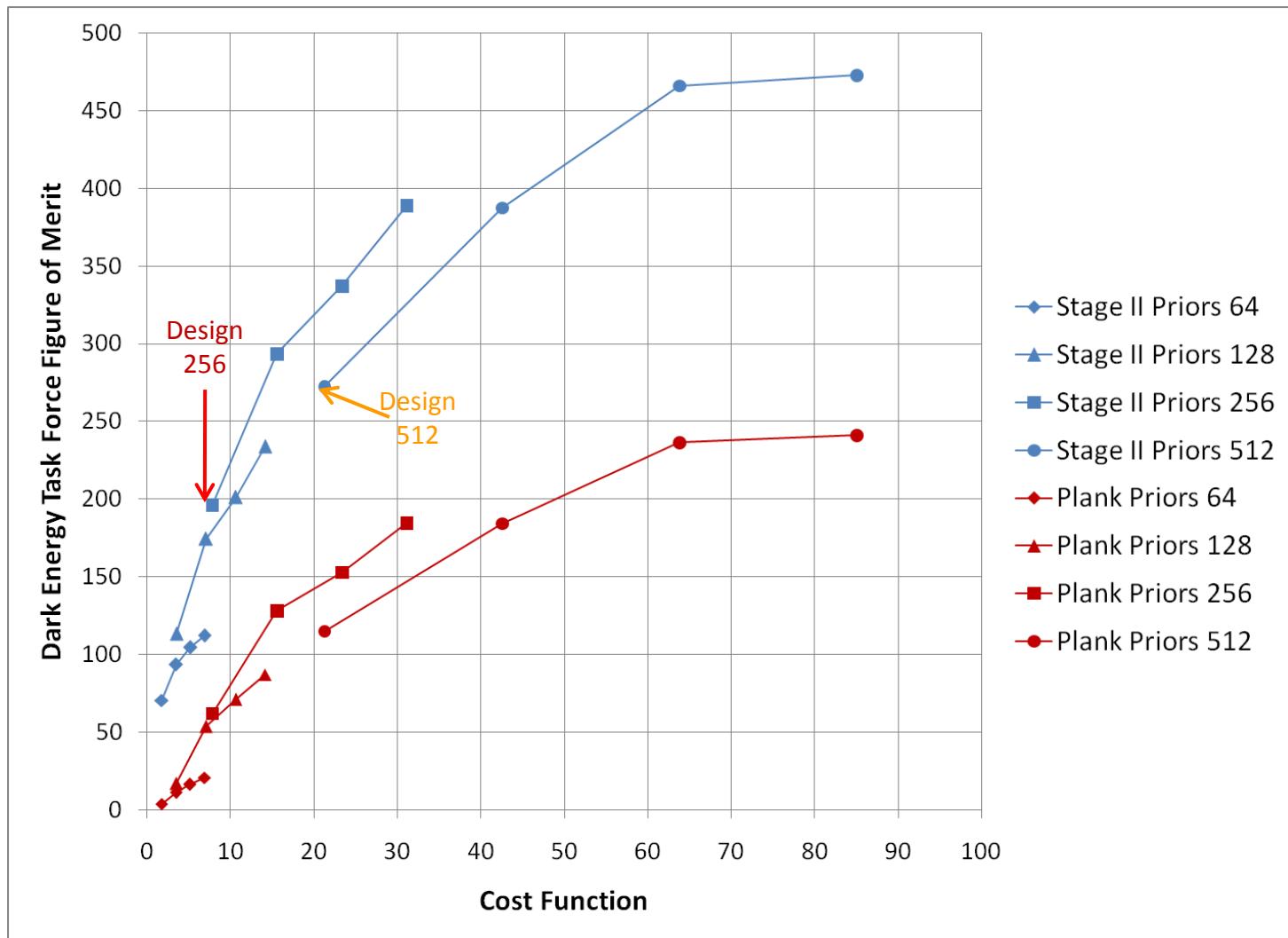
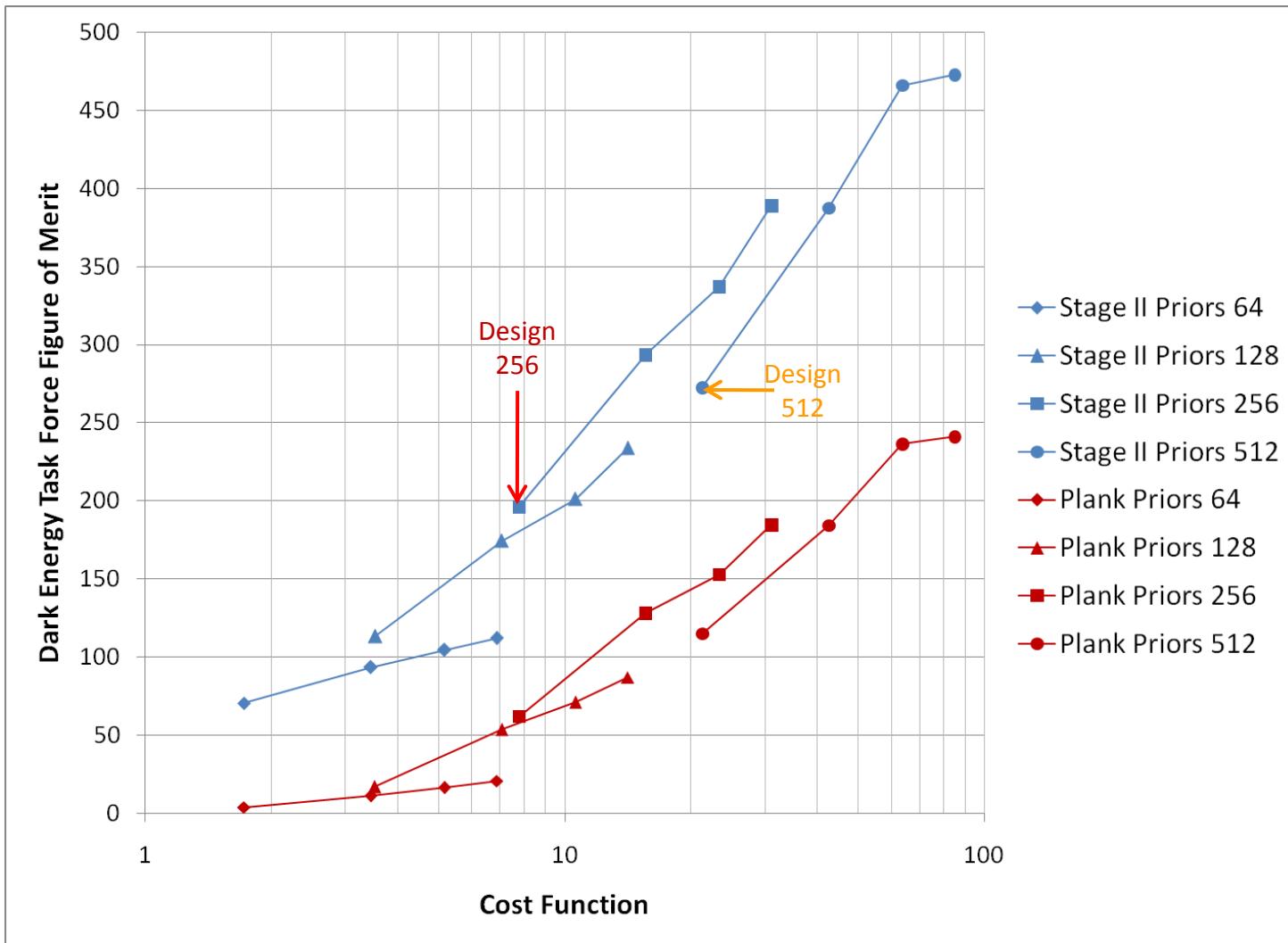
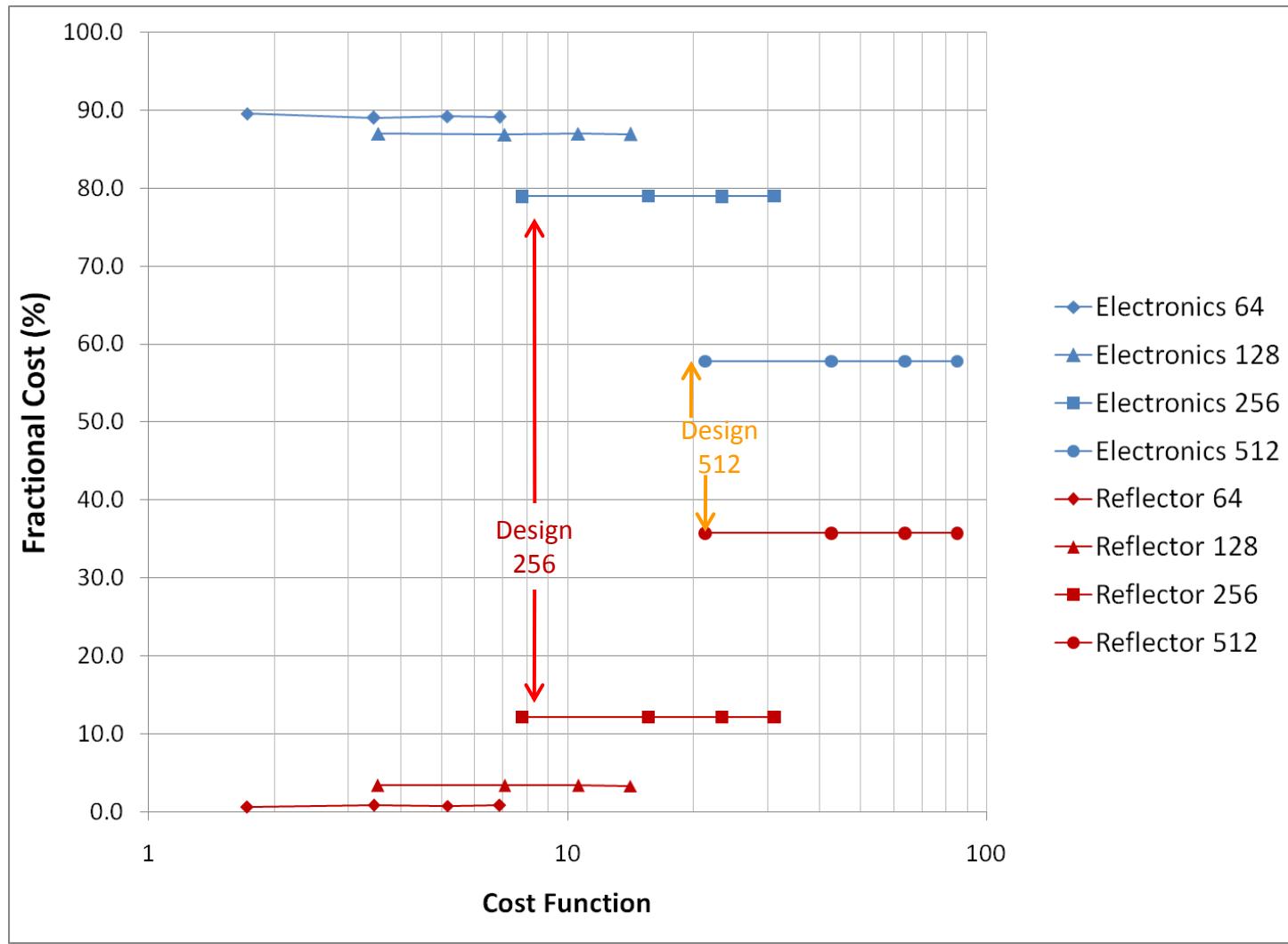


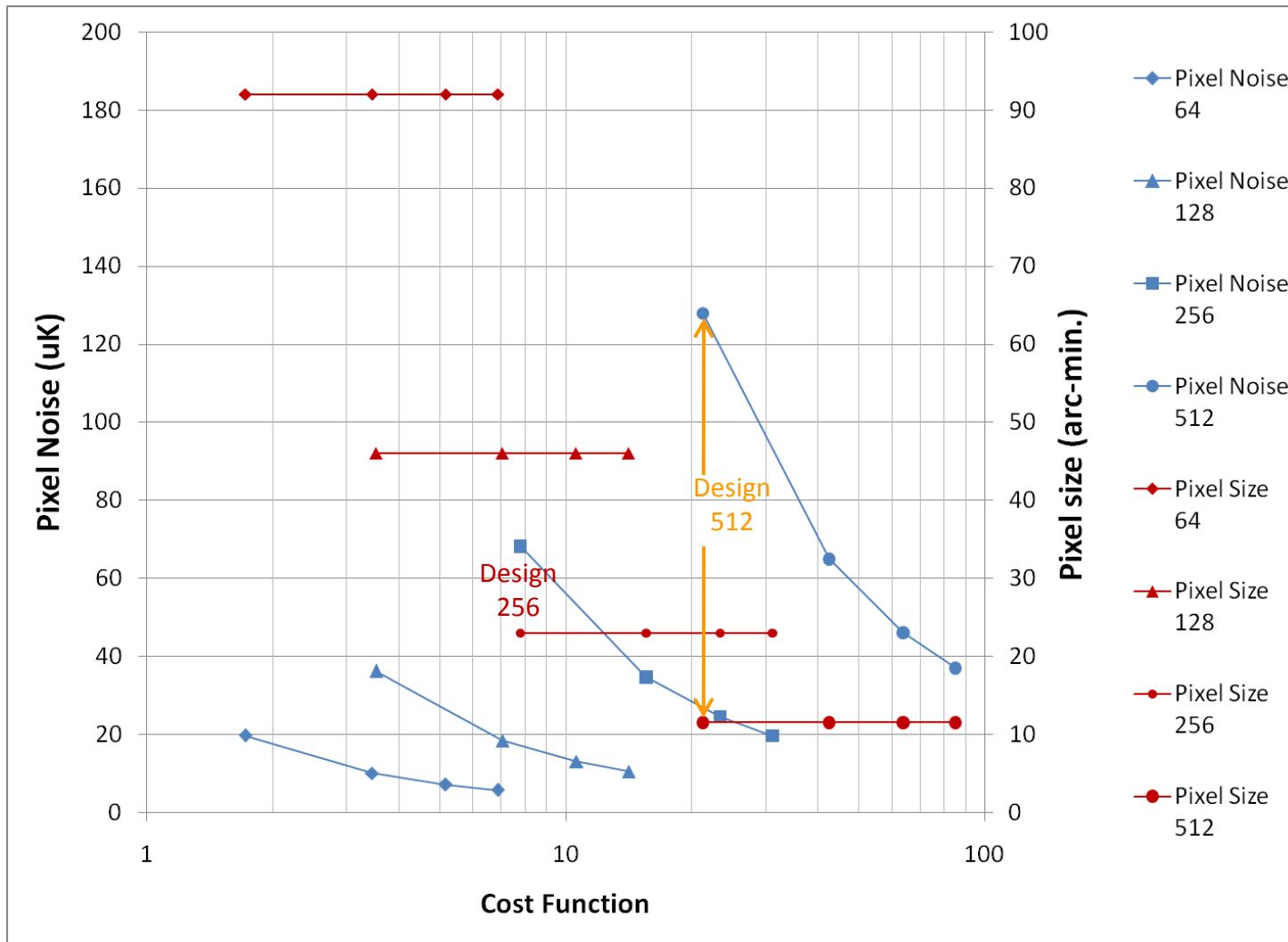
Figure of Merit vs Cost



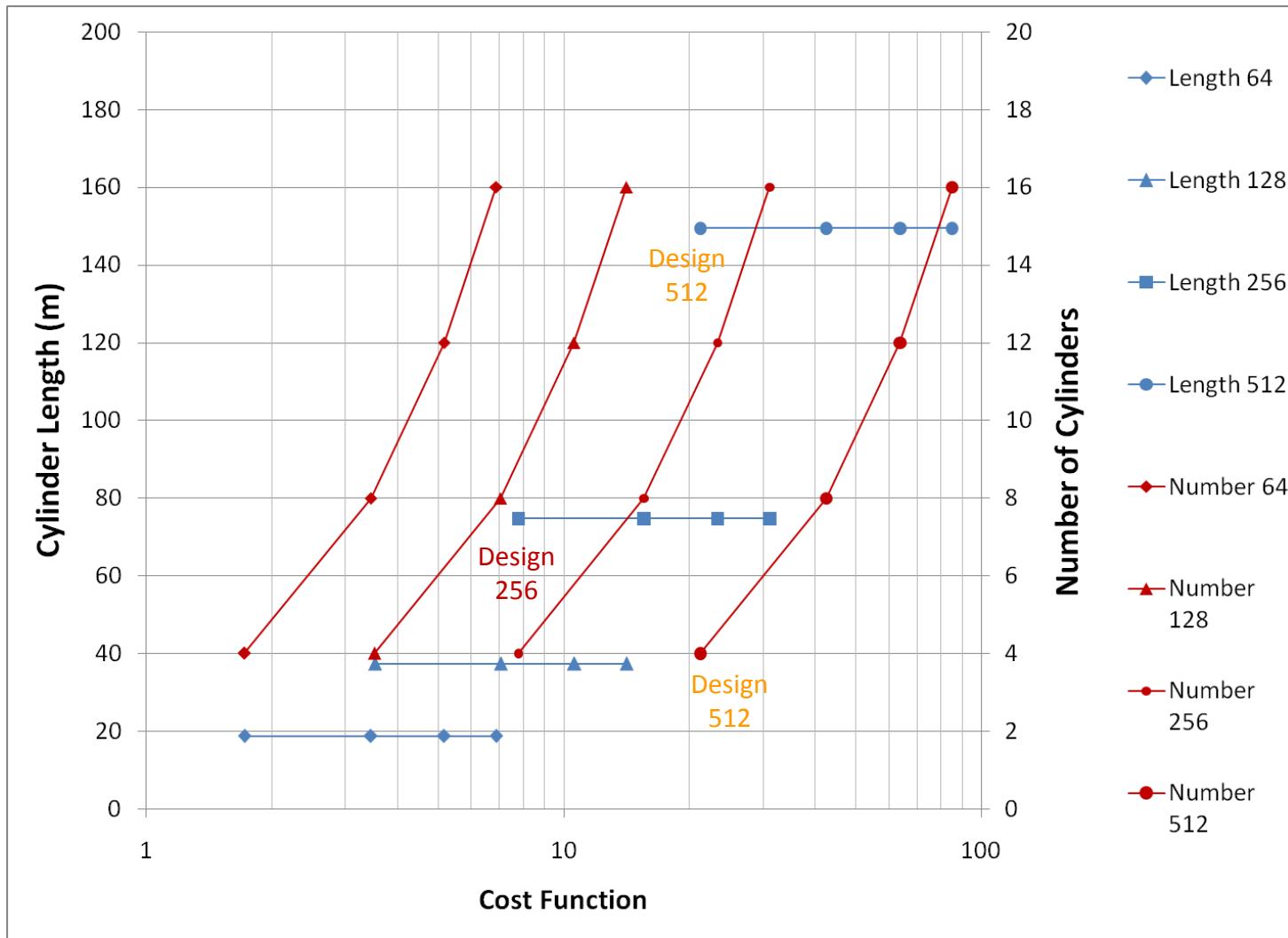
Fractional Cost



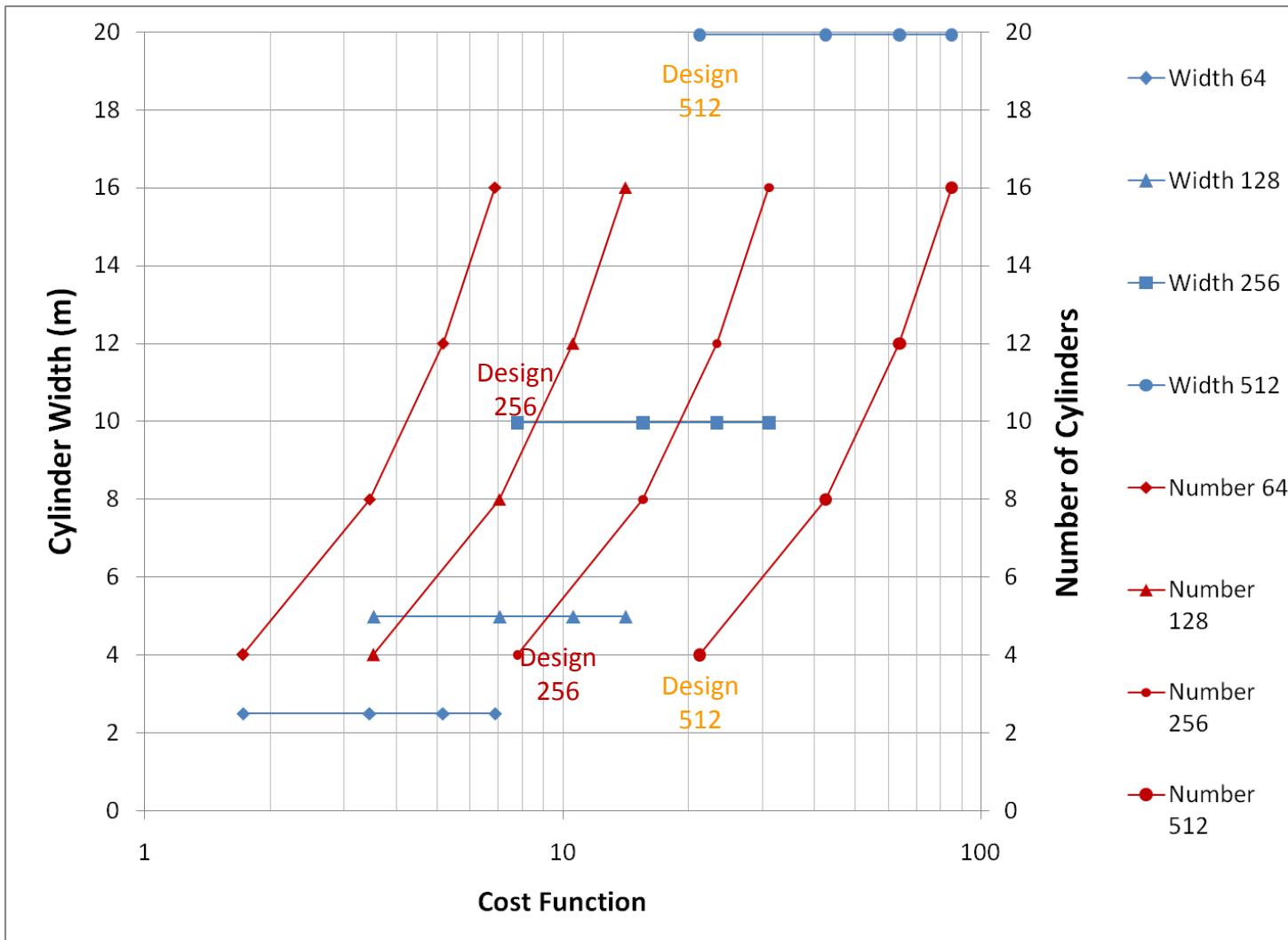
Pixel Noise and Resolution



Cylinder Length



Cylinder Width



Conclusions

- We believe that the CRT is a lower cost and more reliable choice as an intensity mapping instrument
- A Dark Energy Task Force Figure of Merit of
 - 200 can be obtained with a CRT that “costs” ~8M\$
 - 270 can be obtained with a CRT that “costs” ~21M\$

